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Phytodesalination: a Solution for Salt-affected Soils in Arid and Semi-arid Regions

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Abstract: The present work is a survey of several phytodesalination investigations carried out in our laboratory showing the ability of some obligate halophytes to desalinize their rhizosphere through field and greenhouse experiments. This evaluation was based on (i) the decrease in soil salinity, sodicity, and sodium concentration, (ii) phytodesalination (PHD) capacity of the halophyte, and (iii) the ability of a glycophyte to grow on the desalinized soil. In field experiments, we found that tufts of perennial halophytes such as *Tecticornia indica* (Willd.) subsp. *indica* and *Suaeda fruticosa* (Forssk.) offer to numerous annual glycophytes a microhabitat favorable for their development. This was probably due to two major factors: sodium accumulation within the halophyte shoots and the facilitation of its leaching in the soil. We estimated PHD capacity in a Tunisian sabkha at about 0.65 t Na^+. ha^{-1} in summer and 0.75 t Na^+. ha^{-1} in winter. In greenhouse experiments, tested halophytes (*T. indica*, *S. fruticosa*, and *Sesuvium portulacastrum*) showed noticeable PHD capacity under non-leaching conditions (about 1 t Na^+ ha^{-1} in the case of *S. portulacastrum*). On soil taken from inside halophyte tufts, glycophyitic *Medicago* species exhibited higher biomass production than on soil taken from outside tufts. In addition, the cultivation of *Hordeum vulgare* L. (test culture) on saline soil previously desalinized by *S. portulacastrum* showed that the decrease in soil salinity and sodicity was beneficial to coleoptile emergence as well as to biomass production, tissue hydration, sodium accumulation, and potassium acquisition.

Key Words: Arid and semi-arid regions, Halophytes, Non-leaching conditions, Phytodesalination capacity

1. Introduction

It was postulated that salt-affected soils cover about 6% (more than 800 million ha) of the world lands, which is mainly due to natural causes (salt accumulation over long periods of time in arid and semi-arid regions) or to human-induced causes that affected in 2008 about 2% (32 million ha) of the dryland-farmed areas and 20% (45 million ha) of the irrigated lands in the world (Munns and Tester, 2008). To overcome this problem, several authors (Zhao *et al*., 2001, 2005; Graifenberg *et al*., 2003; Tester and Davenport, 2003; Ravindran *et al*., 2007; Rabhi *et al*., 2009, Rabhi *et al*., 2010a, Rabhi *et al*., 2010b) have been encouraging this biological approach proving the efficiency of Na^+-hyperaccumulating plants to desalinize the soil on which they are cultivated, especially in arid and semi-arid regions, where low precipitations and inappropriate irrigation systems are unable to leach salts from the rhizosphere. Soil phytodesalination is based on the capacity of some halophytes to accumulate enormous sodium quantities in their shoots (Rabhi *et al*., 2009, Rabhi *et al*., 2010a, Rabhi *et al*., 2010b). The present work is a survey of several phytodesalination investigations carried out in our laboratory showing the ability of some halophytes to desalinize their rhizosphere through field and greenhouse experiments. This evaluation was based on (i) the decrease in soil salinity, sodicity, and sodium concentration, (ii) phytodesalination (PHD) capacity of the halophyte (sodium quantity accumulated within its shoots per hectare), and (iii) the ability of a glycophyte to grow on the desalinized soil.

2. Materials and Methods

2.1. Field experiment

In this experiment, four different quadrats of 100 m^2 (10×10 m) were chosen for soil and plant sampling in different localities in the salt-affected ecosystem, Soliman sabkha (N-E Tunisia). Whole tufts of the halophytes *Tecticornia indica* (Willd.) subsp. and *Suaeda fruticosa* (Forssk.) were collected for shoot dry weight and sodium concentration determination in HNO_3 (0.5%) extracts. Soil samples of the upper 20 cm were collected from inside and outside halophyte tufts and were analyzed for ECe and soluble sodium concentration in saturation paste extracts. In both soil and plant extracts, Na concentration was measured with a Corning spectrophotometer. Halophyte productivity (Shoot dry weight per hectare) and their phytodesalination capacity (PHD capacity = Productivity * Shoot Na concentration) were estimated by a multiplication

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of mean values of the four quadrats by 100.

2.2. Greenhouse experiment under non-leaching conditions

Seedlings of *Sesuvium portulacastrum* L., *T. indica* and *S. fruticosa* with the same weight were cultivated in pots filled each with 8 kg saline sodic soil taken from the borders of Soliman sabkha. For each species, five plants were grown per pot and irrigated with tap water at almost 50% of the soil field capacity. Pots with no plantation were considered as control. After 170 days, plants were harvested and their shoots were weighed and analyzed. Soil samples were also taken and analyzed. Halophyte productivity was estimated through their density (5 plants per pot), their shoot dry weight, and pot surface.

2.3. Test-culture experiment

The substrate used in this experiment was a loamy sand (SAR = 5.7 (mmol $l^{-1})^{1/2}$ and ECe = 2.4 dS m^{-1}). For plant material, we used *S. portulacastrum* as phytodesalinating halophyte and *Hordeum vulgare* L. (var. Manel) as glycophyte for the test-culture. The phytodesalination culture was performed under non-leaching conditions and lasted 189 days. Three treatments were used: Control (irrigated with tap water from the beginning to the end of the experiment), Salinized (Watered with NaCl solution up to a soil sodium percentage of 0.25% then irrigated with tap water until the end of the experiment), and Phytodesalinized (salinized soil on which *S. portulacastrum* plants were cultivated and irrigated with tap water until the end of the experiment). The test-culture was realized by sowing *H. vulgare* seeds in pots of the three treatments after harvesting the halophyte and mixing the soil of each pot separately. Then, pots were irrigated with tap water for 30 days. As for the two previous experiments, at the end of each culture, soil and plant samples were taken and analyzed.

3. Results and Discussion

3.1. Field experiment

ECe values were 2.8-4.9 times higher in outside-tuft than in inside-tuft soil in both July and February samples (**Table 1**). In inside-tuft soil, the decrease between summer and winter was 42-57%. The same tendency was found in soluble sodium concentrations. This suggests Na^+ removal by the halophytes either through its accumulation in shoots and/or through facilitating its leaching.

T. indica productivity (7.42 t DW ha^{-1}) was shown to be several times that of *S. fruticosa* (2.19 t DW ha^{-1}; Table 1). This was due to (i) the higher capacity of the former to produce shoot phytomass, and (ii) to its noticeable predominance within the ecosystem. In winter, both halophytes experienced high shoot sodium concentration, whereas in summer, a marked decrease was found in *S. fruticosa*.

Table 1. Soil ECe and soluble Na concentration and halophyte productivity and phytodesalination (PHD) capacity measured in summer 2007 and in winter 2008. Values are means of 6 replicates. Means followed by the same letter are not significantly different according to Duncan's test at 5%. Soil and plant samples were taken from outside halophyte tufts (OT) and inside *T. indica* (TI) and *S. fruticosa* (SF) ones.

	Summer			Winter		
	OT	TI	SF	OT	TI	SF
ECe (dS. m^{-1})	75.6d	27.2b	25.4b	57.4c	11.8a	14.8a
Soluble Na (%)	0.63c	0.44b	0.38b	0.64c	0.19a	0.18a
Productivity (t DW. ha^{-1})	0.00a	7.42c	2.19b	0.00a	7.42c	2.19b
PHD capacity (t Na^+. ha^{-1})	0a	0.64c	0.04b	0a	0.75c	0.22b

Table 2. ECe and soluble Na concentration of a naturally salt-affected soil and plant productivity and phytodesalination (PHD) capacity after a 170-day culture of *S. portulacastrum*, *T. indica* and *S. fruticosa*. For productivity and PHD capacity, values are means of 6 replicates. Values followed by the same letter are not significantly different according to Duncan's test at 5%.

	S. portulacastrum	*T. indica*	*S. fruticosa*
ECe (% of the control)	29	35	45
Na^+ (% of the control)	46	52	61
Productivity (t DW ha^{-1})	6.64b	2.32a	2.04a
PHD capacity (t Na^+ ha^{-1})	0.99b	0.26a	0.36a

Accordingly, we observed higher phytodesalination (PHD) capacity (sodium quantity accumulated in shoots per hectare) in *T. indica* than in *S. fruticosa* (**Table 1**). The whole quantity of sodium removed by the two halophytes was 0.69 and 0.97 t ha^{-1} in July 2007 and February 2008, respectively.

This experiment revealed two major findings: 1) Phytodesalination depends on plant species, soil properties (salinity, sodicity, and porosity), and climatic conditions (mainly rainfall) (Rabhi *et al*., 2010a). 2) The removed sodium quantity is not exclusively accumulated in halophyte shoots since a part can be due to leaching process (Qadir and Oster, 2004; Rabhi *et al*., 2009; Rabhi *et al*., 2010a). For this reason, we carried out a greenhouse investigation under zero-leaching conditions.

3.2. Greenhouse experiment under non-leaching conditions

We found a high capacity in the three halophytes to extract soil sodium and to decrease soil salinity. ECe was reduced to 29, 35, and 45% of the control by *S. portulacastrum*, *T. indica* and *S. fruticosa*, respectively (**Table 2**). Our results revealed also similar variations in the soil soluble sodium concentrations, indicating the high ability of the three species to remove this

Table 3. ECe, soluble Na concentration, and SAR of the upper 10 cm of an experimentally salt-affected soil after a 189-day culture of *S. portulacastrum*. Values are expressed as % of the control.

	Salinized	Phytodesalinized
ECe	299	232
SAR	862	580
Soluble Na^+	474	320

cation from the soil.

Our estimations showed considerable productivity in the three halophytes, mainly *S. portulacastrum* that was able to produce 6.6 t DW ha^{-1}. High PHD capacities were also observed in the three halophytes, the highest being found in *S. portulacastrum* (0.99 t Na ha^{-1}, which is the equivalent of 2.5 t NaCl ha^{-1}; Table 2).

From this work, we concluded that *S. portulacastrum* was the most promising halophyte. Ravindran *et al*. (2007) estimated its PHD capacity after a 4-month culture to 0.47 t NaCl ha^{-1}. These findings are interesting and encouraging, however, the decrease in soil salinity and sodicity does not necessarily ensure an amelioration of a glycophyte if cultivated on. Therefore, we performed a test-culture to check whether the glycophyte *H. vulgare* can be grown on a phytodesalinized soil.

3.3. Test-culture experiment

The soil salinization led to an increase of ECe in the upper 10 cm of the soil (299% of the control; **Table 3**). SAR and soluble sodium concentration reflected the results of ECe; they were increased in the salinized soil to 862 and 474% of the control, respectively. These high values of ECe, SAR, and soluble sodium concentration were reduced in the phytodesalinized treatment to 232, 580, and 320% of the control, respectively. This confirms the idea of a high PHD capacity in the shoot succulent halophyte, *S. portulacastrum*.

Our findings were supported by a noticeable amelioration of *H. vulgare* coleoptile emergence, growth, tissue hydration, sodium accumulation, and potassium status as grown on phytodesalinized soil (**Table 4**). In literature, little is known about test-cultures. Abdelly *et al*. (1995) took soil from inside and outside perennial halophyte tufts and grew *Medicago* species (glycophytes) on. They observed that on soil taken from inside halophyte tufts, glycophyitic *Medicago* species exhibited higher biomass production than on soil taken from outside tufts. Ecologically speaking, perennial halophytes offer to numerous annual glycophytes a microhabitat suitable for their development (Abdelly *et al*., 1995).

This experiment showed also that salinity and sodicity in the layer 10-20 cm of the phytodesalinized soil were increased due to the halophyte root effects (non-shown data). Indeed, vegetative bioremediation of the upper horizon was due not only to phytodesalination but also to sodium leaching to the lower horizon. According to Qadir and Oster (2004), the decrease in soil sodium concentration, and consequently soil salinity/sodicity, occurs in two steps: 1) its release from cation exchange sites through an increase of CO_2 partial pressure within the root zone (and root proton release in the case of N_2-fixing plants) then 2) its removal from the upper horizons through leaching and/or phytodesalination.

Table 4. Final percentage of coleoptile emergence, biomass production, tissue hydration, and sodium and potassium concentrations in *H. vulgare* plants grown on salinized and phytodesalinized soils. Values are expressed as % of the control.

	Salinized	Phytodesalinized
Coleoptile emergence	44	74
Plant biomass	8	41
Shoot water content	64	81
Shoot sodium concentration	138	98
Shoot potassium concentration	46	62
Root water content	44	67
Root sodium concentration	113	101
Root potassium concentration	43	42

4. Recommendation

Phytodesalination is an emerging technique that can be used to cope with salinity/sodicity problems in arid and semi-arid regions. However, its application requires an optimization, including the choice of the convenient halophyte and the season of its culture. In addition, extremely sodic/saline soils cannot be phytodesalinized. Plants used for phytodesalination purposes can have several post-harvest uses (fodder, biofuel production, oil extraction, essential oil extraction, medicinal uses…) and can thus have two simultaneous beneficial utilizations.

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